Side-Face Effect of a Dielectric Strip on Its Optical Properties

Wenbo Sun, Bing Lin, Yongxiang Hu, Zhenhui Wang, Yunfei Fu, Qian Feng, and Ping Yang

***Abstract*—Light scattering by horizontally oriented platelike particles under normal incidence, such as ice plates or tree leaves under spaceborne lidar or radar waves, needs to be investigated for remote sensing of cirrus clouds or vegetation canopies. The solutions from the conventional geometrical ray tracing method for the scattering of electromagnetic waves by these particles are quite inaccurate because of the singularity problem that is inherent to this method. The scattering properties of large horizontally oriented platelike particles are usually approximated by using physical optics or electromagnetic wave theory while ignoring the side-face effect of the plates. In this paper, to examine the effect of side faces on light scattering by platelike particles, a 2-D finite-difference time-domain technique is applied to calculate light scattering by horizontally oriented ice and leaf strips under normal or quasi-normal incidence. It is found that for moderate-sized strips, the side faces of the particles scatter a significant amount of energy, resulting in strong maxima in the scattering phase function at certain scattering angles. By ignoring the effect of side faces, the scattering phase functions derived from electromagnetic wave theory have significant errors for small or moderate-sized strips. However, the ratio of the amount of energy scattered by the side faces to the total scattered energy decreases with the increase of strip width. When the size parameter of the strip is in the limit of geometric optics, the side-face effect is reduced to a negligible amount. However, even in this case, the polarization degrees from the approximation solutions of physical optics or electromagnetic wave theory ignoring the side-face effect still have large errors.**

***Index Terms*—Finite-difference time domain (FDTD), scattering, side-face effect, strip.**

I. Introduction

RECENT studies [1], [2] based on the observations made by a spaceborne lidar show that a significant amount of ice crystals in ice clouds is horizontally oriented. Similarly oriented tree leaves are also very common in nature. Light scattering by quasi-horizontally oriented ice plates or tree leaves under normal or quasi-normal incidence needs to be modeled for quantitative remote sensing of cirrus clouds or vegetation canopies. Although many analytical or semianalytical methods have been developed to solve light scattering by various regularly shaped particles [3]–[7], the solution of light scattering by platelike particles in nature is still in progress due to the nonspherical shapes, large sizes, or special orientations of these particles. Accurate numerical models, such as the 3-D finite-difference time-domain (FDTD) technique [8]–[13] and the discrete dipole approximation [14], can be used for arbitrary particle shapes, but the applications of these methods are essentially limited to the resonant size-parameter regime due to the limit of current computational resources in terms of computer CPU speed and memory. On the other hand, the conventional geometric ray tracing method has been used to investigate the

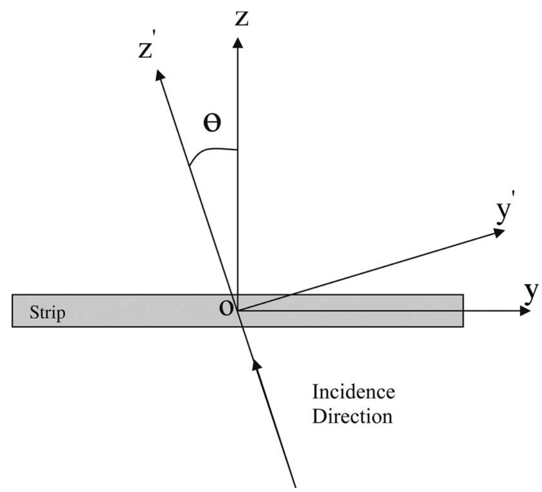

Fig. 1. Cross section of a horizontally oriented strip and the basic geometry of light scattering by the strip that lies on the $x-y$ plane of the xyz coordinates with the center of the strip at $z=0$ (the strip is infinitely long in the x-direction). Also shown in this figure is the $xy'z'$ coordinate system used for defining the incidence direction and deriving the single-scattering properties.

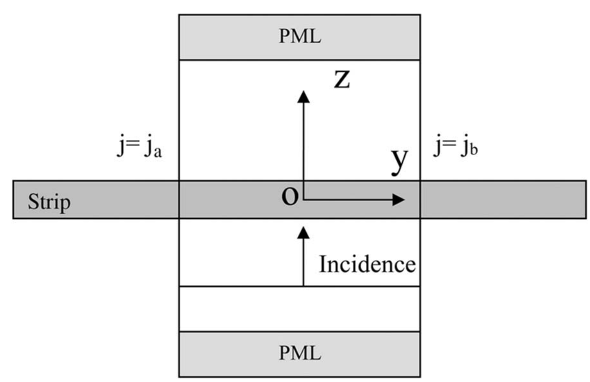

Fig. 2. Two-dimensional FDTD modeling for the fields inside the strip as part of an infinitely large slab. The incident electromagnetic waves propagate along $+z$-direction.

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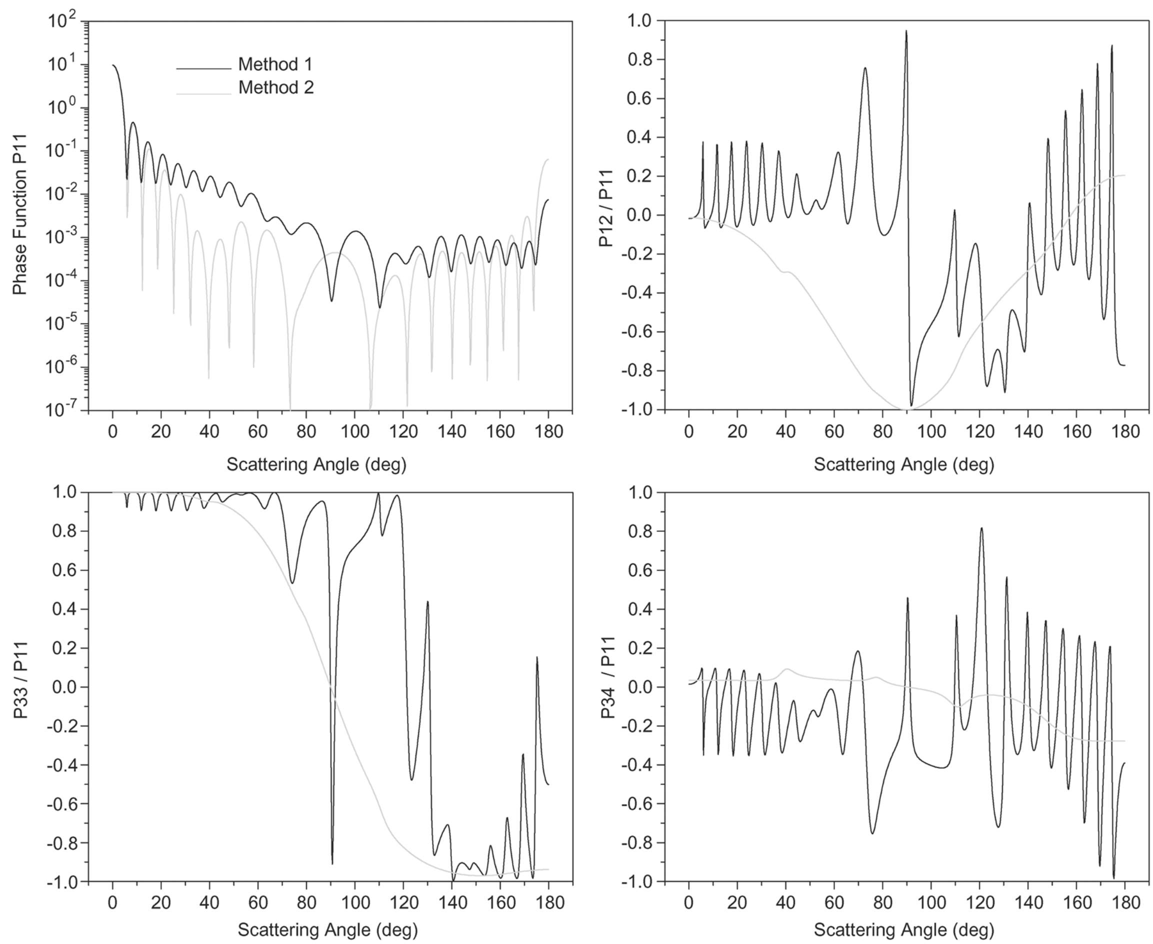

Fig. 3. Light-scattering phase matrix elements of an ice strip with a width of $D = 50\ \mu$m and a thickness of $h = 10\ \mu$m. Light is incident normally on the strip.

single-scattering properties of large (relative to incident wavelength) ice crystals under both random [15]–[18] and horizontal [19] orientation conditions. However, this method may be quite inaccurate in the case of quasi-horizontally oriented ice plates or leaves even if the size parameters are in the geometric optics regime, due to the singularity problem that is inherent to this technique [20]. Therefore, light scattering by large thin disks is usually approximately solved by physical optics with the assumption of an infinitely large slab [21], [22] or by electromagnetic wave theory while ignoring the side-face effect of the plates [20], although for small or tenuous discs, Rayleigh or Rayleigh-Gans approximations are frequently used [23]. To fully understand the optical properties of horizontally oriented platelike particles under normal incidence, it is necessary to investigate the side-face effect on the single-scattering properties of these particles.

This paper examines the effect of side faces on light scattering by platelike particles using the 2-D FDTD technique [24], [25] to calculate the light scattering by quasi-horizontally oriented ice and leaf strips. Although ice and leaf strips have different particle shapes from the natural ice plates or leaves, the physics in the effect of side faces on light scattering for these infinitely long particles should be similar to that for ice plates or tree leaves. Thus, the side-face scattering feature of the infinitely long strips could be a good representative for natural ice plates or tree leaves. The 2-D FDTD method for the calculation of light scattering by horizontally oriented strips is briefly reviewed in Section II. Numerical results and discussions are presented in Section III. Summary and conclusions are given in Section IV.

II. Method

To calculate light scattering by a thin disk, we first calculate the electric fields inside the disk and then use a volume integral to obtain the light-scattering properties of the particle [12]. In this paper, we employ two approaches to calculate the electric fields inside a dielectric strip. The first approach (Method 1) is a regular FDTD solution of the electric fields inside an isolated strip, i.e., fields scattered by the whole strip including the side faces of the strip are accounted for. The second one (Method 2) is to assume the strip to be a part of an infinitely large slab; the inside fields are calculated by the FDTD algorithm with periodic boundary conditions in the stretch directions of the slab [26]. Note that, for infinitely large slab, the inside fields can also be calculated by other methods such as physical optics or geometric optics. Similar to the electromagnetic wave theory approximation [20], the second approach is an approximate method which neglects the effect of side faces of the strip. By comparing the results from the two approaches, we can evaluate the side-face effect on light-scattering properties of platelike particles.

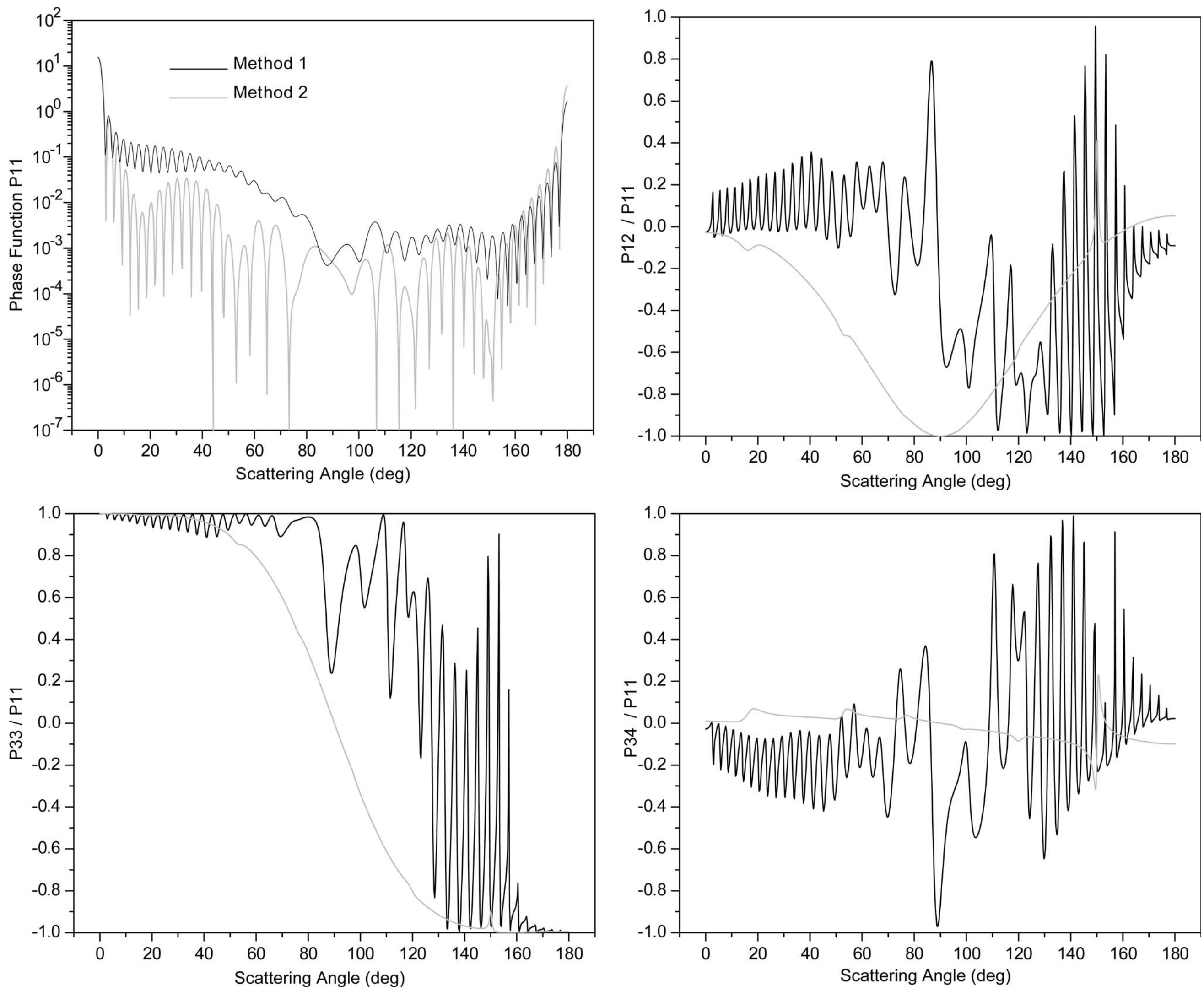

Fig. 4. Same as in Fig. 3, but for a larger strip with a width of $D = 100$ μm and a thickness of $h = 15$ μm.

To calculate the electric fields inside the isolated strip, we employ the 2-D FDTD program [24] with a perfectly matched layer (PML) absorbing boundary condition (ABC) [27]. Because the FDTD algorithm can accurately calculate light scattering by particles of arbitrary shapes, the 2-D FDTD program developed in [24] is directly applied to calculate light scattering by horizontally oriented strips under normal or quasi-normal incidence without any change. Fig. 1 shows the cross section of a horizontally oriented strip and the basic geometry of light scattering by the strip that lies on the $x-y$ plane of the xyz coordinates with the center of the strip at $z = 0$ (the strip is infinitely long in the x-direction). Also shown in this figure is the $xy'z'$ coordinate system used for defining the incidence direction and deriving the single-scattering properties. Because the strip is infinitely long in the x-direction, the calculation is reduced to a 2-D scattering problem. Thus, we let the xyz and $xy'z'$ coordinate systems share the same x-axis. The incidence direction is fixed in the $+z'$-direction in the $xy'z'$ coordinates. The $xy'z'$ coordinate system can rotate around the x-axis so that an oblique incident direction can be achieved. However, in this paper, we focus on horizontally oriented platelike particles under the normal or quasi-normal incidence, where the singularity problem of geometric ray tracing light-scattering models exists. In the FDTD calculation, each spatial cell is assigned to be $1/N$ of the wavelength of the incident wave, where N is about 20 times the real part of the refractive index. The time step is set to be one half of the time that the wave can travel through a single cell. The computational domain is truncated by the PML ABC, which absorbs all outgoing electromagnetic waves impinging on these boundaries and overcomes the artificial reflection from the boundaries. In order to obtain differential values of electromagnetic fields, magnetic and electric field components are evaluated alternatively at different temporal and spatial grid points with half time-step and half cell-size differences, respectively. With a time step updating the FDTD electromagnetic field equations, the near fields in the frequency domain can be obtained from the fields in the time domain via a discrete Fourier transform. The single-scattering properties, including the scattering and absorption efficiencies and the normalized scattering phase matrix elements (Mueller matrix elements), are calculated by using the near fields in the frequency domain inside the strip.

For the calculation of the fields inside the strip as part of an infinitely large slab, we consider the strip as one periodic part of

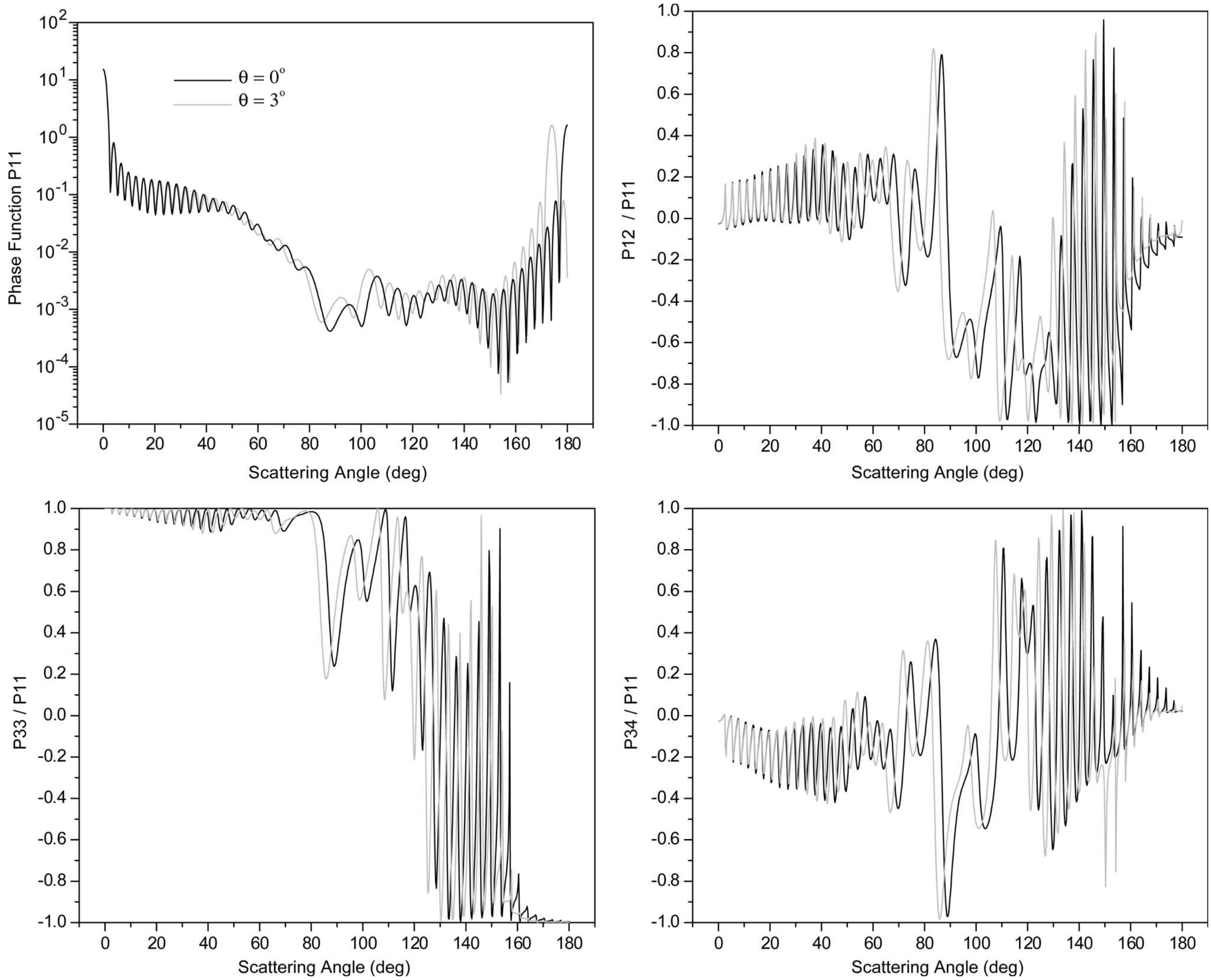

Fig. 5. Comparison of light-scattering phase matrix elements from two ice strips with the same dimensions as in Fig. 4, but one is under a normal incidence and the other is tilted with an incidence angle of 3°.

the slab. The fields inside this period of the slab are calculated by the 2-D FDTD program with periodic boundary conditions in the stretch directions of the slab. The light-scattering properties of the strip are derived by a volume integration of the fields inside the calculated single period.

Fig. 2 shows the 2-D FDTD modeling for the fields inside the strip as part of an infinitely large slab. We assume that the incident electromagnetic waves propagate along the z-direction (i.e., normal incidence and z and z' share the same direction). In the incidence direction, the computational domain is truncated by the PML ABC. At sides $j = j_a$ and j_b, periodic boundary conditions are applied. For example, for the E_x-polarized incidence case, the periodic boundary conditions for the field components E_x, H_y, and H_z simply are

$$H_y^{n+1/2}(j_b, k+1/2) \leftarrow H_y^{n+1/2}(j_a, k+1/2) \quad (1a)$$
$$H_z^{n+1/2}(j_b+1/2, k) \leftarrow H_z^{n+1/2}(j_a+1/2, k) \quad (1b)$$
$$E_x^{n+1}(j_b, k) \leftarrow E_x^{n+1}(j_a, k) \quad (1c)$$

where the arrow "←" denotes the assignment of the value of the field component at its right side to the field component at its left side, n is the time step, and j and k are the coordinates of the field components in the FDTD spatial grid.

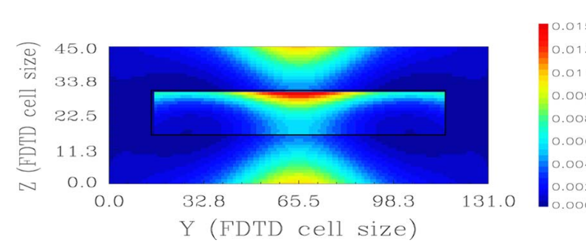

Fig. 6. FDTD-simulated instantaneous electric field around an ice strip of $x = \lambda D/\lambda = 10$ and aspect ratio $\alpha = 10$. The incidence is a plane pulse, with electric field polarized in a normal direction to the yoz plane in Fig. 1 and propagates normally to the ice strip. The wave is initiated on a rectangular locus two spatial cells away from the strip; thus, the field within the locus is the total field (i.e., incidence field + scattered/transmitted field), whereas the field outside is only the scattered field. The figure shows the electric field intensity at the 500th time step.

III. Numerical Results and Discussions

The present numerical computation is focused on the scattering of light by horizontally oriented ice plates under normal

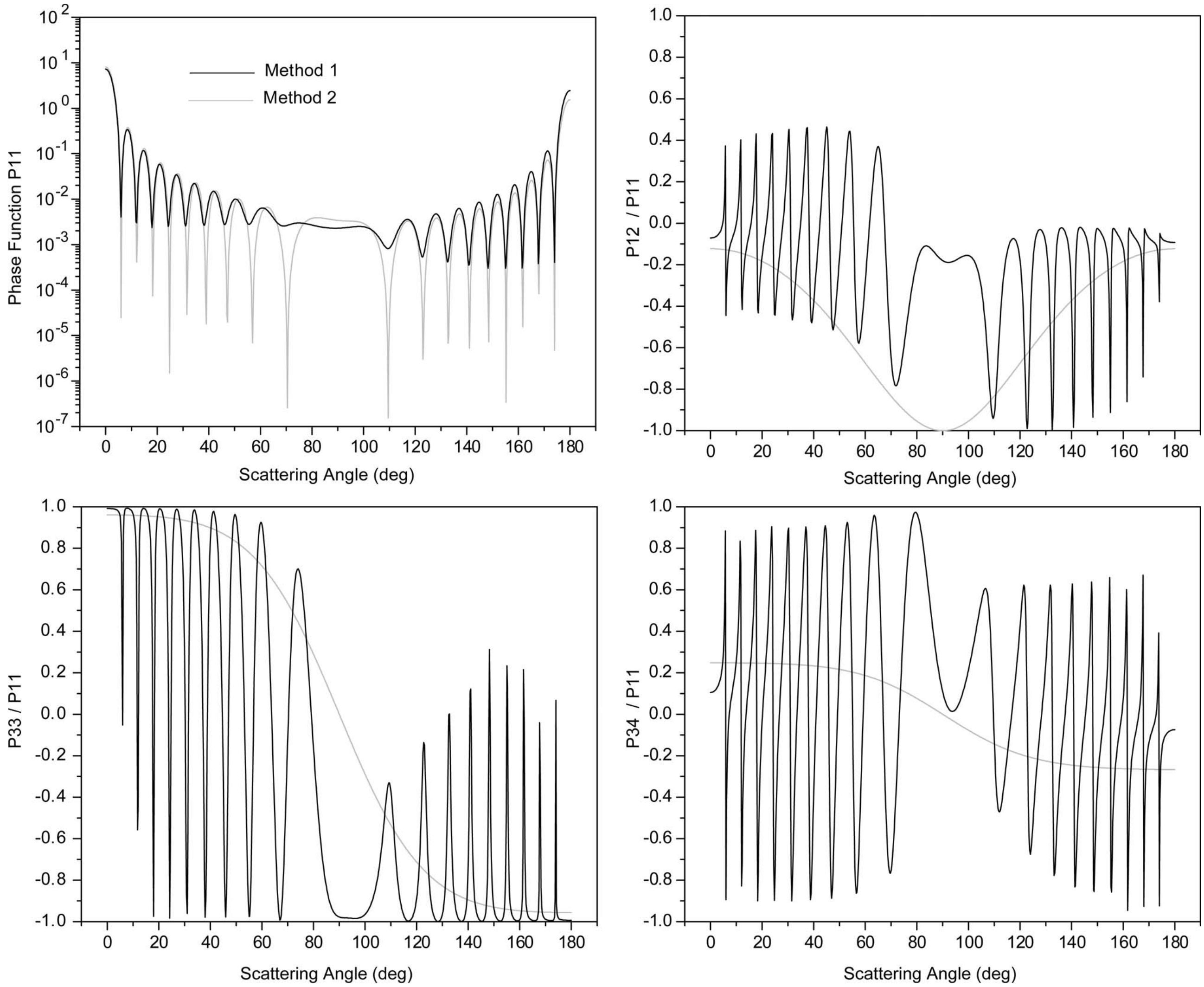

Fig. 7. Phase matrix elements for a leaf strip of size parameter of 30 and aspect ratio of 30 at 37 GHz. At this frequency, a refractive index of $3.46 + 1.075i$ is used for the leaf strip with a water content of 68%. The microwave is incident normally on the strip.

or quasi-normal incidence at 0.532 μm. The refractive index of ice at this wavelength is $1.3117 + i2.6138 \times 10^{-7}$. The FDTD spatial cell size is set to be 1/30 of the incident wavelength. The aspect ratio of the ice strip is defined as $\alpha = D/h$, where D and h denote the width and thickness of the ice strip, respectively. The size parameter of the ice strip is defined as $x = \pi D/\lambda$, where λ is the incidence wavelength.

Fig. 3 shows the light-scattering phase matrix elements of an ice strip with a width of $D = 50$ μm and a thickness of $h = 10$ μm. Light is incident normally on the strip, i.e., $\theta = 0°$. The curves in black are from Method 1 (the approach for isolated strip). The ones in light black are from Method 2 (the approximation which considers the strip as a period of an infinitely large slab). We can see that at side-scattering angles, the normalized conventional phase function P11 from Method 1 is significantly larger than that from Method 2, which means that there is a significant portion of energy scattered due to the side-face effect. For a larger strip with a width of $D = 100$ μm and a thickness of $h = 15$ μm, as shown in Fig. 4, the phase functions from the two methods get closer, particularly at forward- and back-scattering directions. However, we find that the differences of the two methods in the polarization degrees (i.e., P12/P11, P33/P11, and P34/P11) are large for both small and large strips. Ignoring the side-face effect, the polarization degrees from Method 2 are relatively smooth, but those from Method 1 show strong variations with scattering angles due to the complicated interference between the transmitted, diffracted, and reflected waves.

Fig. 5 shows the comparison of light-scattering phase matrix elements from two ice strips with the same dimensions as in Fig. 4, but black curves are for a normal incidence, and the light-black curves are for the strip tilted with an incidence angle of 3°. We can see that tilting the strip by 3° shifts backscattering peak from a scattering angle of 180° to $\sim$174°, but the side-face scattering pattern is not significantly changed.

Fig. 6 shows the FDTD-simulated instantaneous electric field around an ice strip of $x = \pi D/\lambda = 10$ and aspect ratio $\alpha = 10$. The incidence is a polarized plane pulse with electric field $E = \exp[-((n/60) - 5)^2]$, where n is the time step. The wave is initiated on a rectangular locus two spatial cells away from the strip; thus, the field within the locus is the total field (i.e., incidence field + scattered/transmitted field), whereas

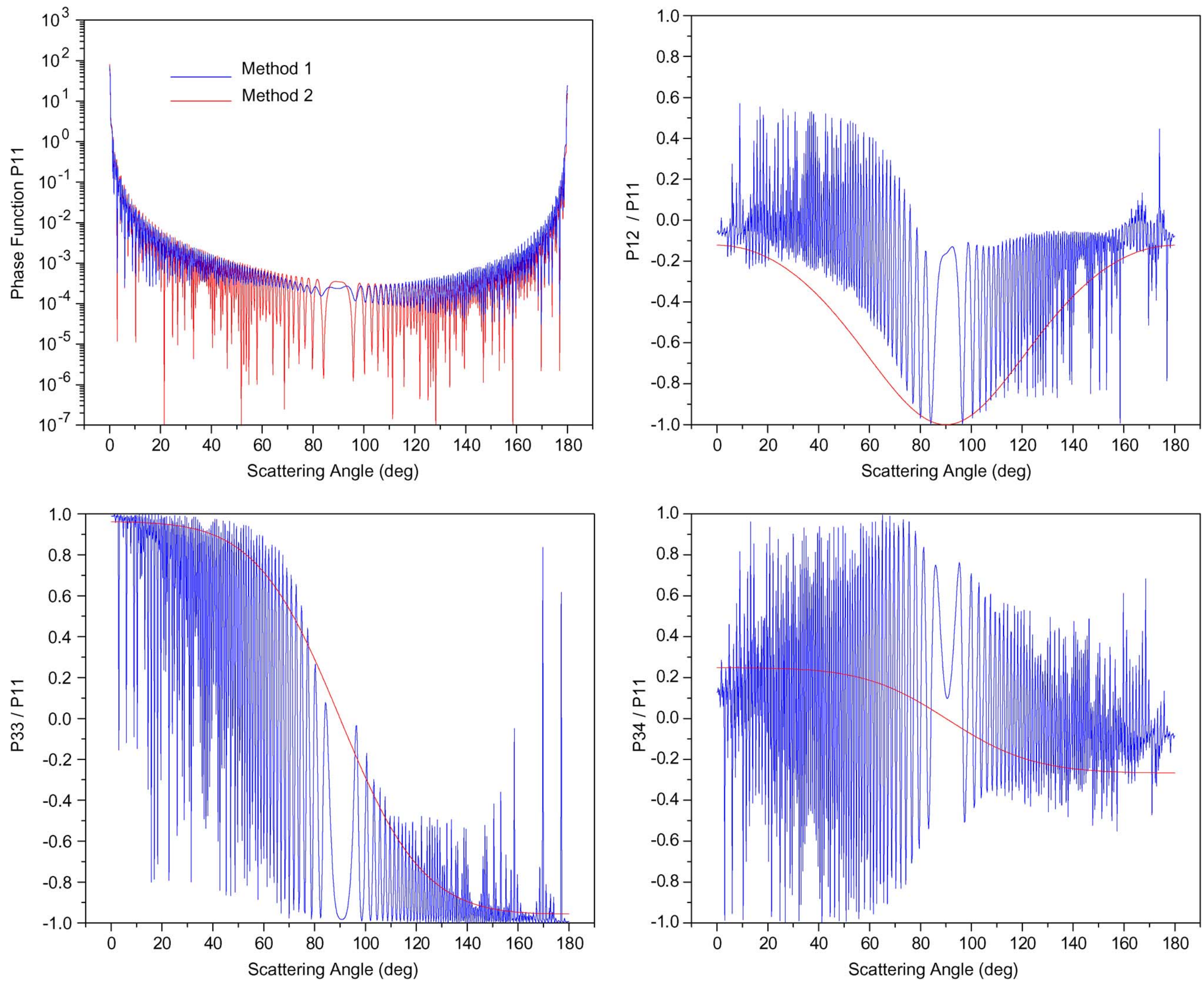

Fig. 8. Same as in Fig. 7, but for a larger size parameter of 300.

the field outside is only the scattered field [28]. The wave is polarized in a normal direction to the yoz plane in Fig. 1 and propagates normally to the ice strip. The figure shows the electric field intensity at the 500th time step. The scattered energy rings at the side faces of the strip extend both in free space and inside the ice strip, making the near field much more complicated than the plane parallel waves as for the infinitely large slab. These side-face-caused complicated near fields are the major reason for the strong variations in the scattered polarization degrees and the intensity at side-scattering angles.

For remote sensing of forest, we need to study the electromagnetic wave scattering and absorption by tree leaves [29], including the horizontally oriented leaves under normal incidence. To examine if Method 2 provides good solutions of microwave scattering of leaves, we compare the phase matrix elements for a leaf strip of size parameter of 30 and aspect ratio of 30 at 37 GHz. At this frequency, a refractive index of $3.46 + 1.075i$ is used for the leaf strip with a water content of 68%, and the FDTD spatial cell size is set to be 1/60 of the incident wavelength. Fig. 7 shows that the normalized phase functions from the two methods agree well. However, same as the ice strip case, the polarization degrees depart from each other. When the size parameter increases to 300, as shown in Fig. 8, the normalized phase functions only have little differences, but the disagreement in the polarization degrees of the scattered light is still large. Therefore, for microwave scattering by fresh tree leaves, Method 2 can produce a reliable conventional phase function but fails in the polarization degrees.

The scattering efficiencies (Qs) and absorption efficiencies (Qa) for Figs. 3, 4, 7, and 8 are listed in Table I. For light scattering by ice strips, Method 2 overestimates the scattering efficiency by $\sim$25%. For microwave scattering by tree leaf strips, Method 2 significantly underestimates both scattering and absorption efficiencies.

IV. Summary and Conclusion

This paper examines the side-face effect on light scattering by platelike particles. The 2-D FDTD technique is applied to calculate light scattering of horizontally oriented strips under normal or quasi-normal incidence. It is found that for moderate-sized strips, the side faces of the particles scatter a significant amount of energy, resulting in strong maxima in the scattering

TABLE I
SCATTERING EFFICIENCIES (Qs) AND ABSORPTION EFFICIENCIES (Qa) FOR (FIGS. 3), (4), (7), AND (8)

	Ice		Leaf	
	D/h = 50μm / 10μm		πD/λ = 30, D/h = 30	
	Method 1	Method 2	Method 1	Method 2
Qs	3.815	4.852	1.273	1.005
Qa	7.0e-6	7.0e-6	0.633	0.081
	D/h = 100μm / 15μm		πD/λ = 300, D/h = 300	
	Method 1	Method 2	Method 1	Method 2
Qs	0.678	0.870	1.264	1.009
Qa	9.0e-6	9.0e-6	0.612	0.082

phase function at certain scattering angles. Due to ignoring the side-face effect, the scattering phase functions from the electromagnetic wave theory generally have significant errors for small or moderate-sized strips. With the increase in strip size, the ratio of the side-face-scattered energy to the total scattered energy decreases. When the size parameter of the strip is in the limit of geometric optics, the side-face effect could be reduced to a negligible amount. However, even in this case, the polarization degrees from the approximation solutions ignoring the effect of side faces still have large errors. These results suggest that the classic approach involving infinitely large slab assumption can be used for fast calculation of the conventional phase function for intensity remote sensing, whereas for remote sensing applications using polarized signals such as for the data from the Special Sensor Microwave/Imager, an accurate calculation is still needed [29].

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